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The Implications of Post-Fire Physical Features of Cylindrical 18650 Lithium-Ion Battery Cells

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Abstract. Fire investigators are trained to apply the scientific method to determine the origin and cause of a fire. They look for patterns that indicate the sequence of involvement of available fuel loads, including considering whether a given fuel load contains enough energy to ignite other fuels. It is common knowledge that cylindrical 18650 lithium-ion (Li-ion) battery cells contain significant electrochemical energy and that they have the potential to fail and cause fires, so they are often considered a potential ignition source. The presence of a damaged 18650 cell at a fire scene poses a challenge to fire investigators because regardless of whether the cell is the cause or a victim of the fire, its stored energy can be released energetically, leaving a burn pattern and rapidly involving other fuel loads. It is therefore desirable to identify post-fire physical features on 18650 Li-ion cells that indicate whether they were the cause or a victim of a fire. This work shows that several features have been incorrectly identified in previous investigations. Expulsion of cell contents, crimp deformation, a flat negative terminal, localized damage in the electrode windings, and a hole in the metal casing have been cited as indications that the cell failed and caused a fire. To test these hypotheses, 18650 Li-ion cells at various states of charge (SOC) were burned in a controlled and repeatable manner. Temperatures were recorded and the experiments were documented with still-photography and video. The post-fire condition of each cell was then characterized with radiography (X-ray), computed tomography, and optical imaging. Each of the post-fire physical features in question occurred in non-defective cells that were victims of controlled fires, thereby demonstrating that these features are not valid indicators of fire causation.

Keywords: Lithium ion, Battery, Fire, Failure, 18650, Fire investigation

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1. Introduction

Consumers desire electronic products that have the optimal combination of portability and energy capacity; lightweight but full-featured products that maximize the time between charging are in high demand. Lithium secondary batteries possess a higher energy density than any other currently available chemistry and are able to power high or low drain portable devices for extended periods of time [1]. These advantages have also enabled portable devices that previously required a combustion engine or power cord—such as chainsaws and lawn mowers—to be battery-powered [2]. This has led to their widespread implementation, with lithium secondary batteries powering a broad range of products including notebook computers, tablets, phones, power tools, lawn equipment, and many others.

A diagram of an 18650 Li-ion battery cell is shown in Fig. 1. It is a cylindrical cell, with a nominal diameter of 18 mm and length of 65 mm that contains two electrodes, the cathode and anode, which have different chemical potentials. These electrodes participate in the oxidation-reduction reaction that enables energy storage [3]. During discharge, electrons flow from the anode to the cathode through an external circuit, providing power to that circuit. The anode and cathode are rolled together in the cell, separated by an electronically insulative film referred to as the separator. This stack, known as the electrode windings (or referred to colloquially as the "jelly roll"), is soaked in an ionically conductive electrolyte that allows for the transport of lithium ions within the cell to maintain overall charge balance [4]. Often the electrolyte is composed of a lithium-based salt and liquid organic species. Li-ion batteries can be recharged by applying a voltage in the

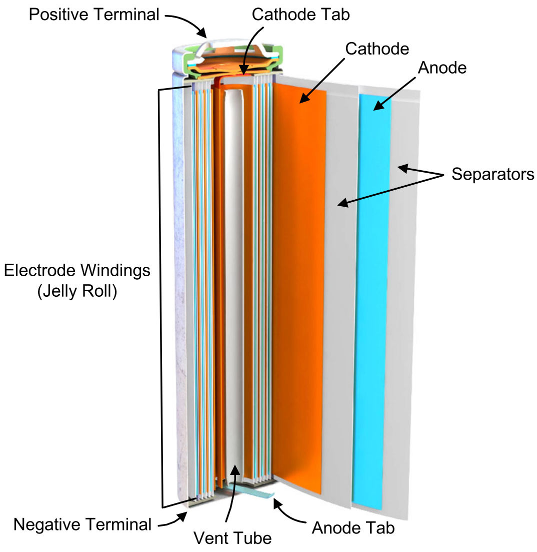

Figure 1. Rendered cross sectional diagram of a typical 18650 Li-ion cell.

reverse, non-spontaneous direction, forcing electrons (and lithium ions) from the cathode to the anode.

Li-ion batteries are the lightest consumer batteries available due to their high energy density, which can be attributed to the low mass of the lithium ion and the high potential difference between the anode and cathode. While alkaline cells generate a potential of 1.5 V and nickel-metal hydride and nickel-cadmium cells generate 1.2 V, Li-ion cells generate between 3.6 and 4.3 V depending on their chemistry [3–5]. Each charge carrier therefore has greater potential energy, as given by the Gibb's free energy (ΔG):

$$\Delta G = nF\Delta V \tag{1}$$

where n is the number of electrons transferred, F is the Faraday constant, and ΔV is the difference in voltage between the cathode and anode [6]. This means the energy density of a cell increases when the cell's positive and negative electrodes have a greater voltage difference.

With high energy density comes safety concerns, as Li-ion cells can enter thermal runaway and produce flaming combustion that can result in personal injury or property damage [7]. Thermal runaway occurs when the heat generated by a cell exceeds the heat being dissipated [8]. It can be initiated by several events, including overcharging, overheating from an external source [9], and an external or internal short circuit [7]. An internal short circuit can be caused by a manufacturing defect, post-manufacture physical damage, or excessive temperatures that cause the cathode and anode to make contact. An external short circuit occurs when a low-resistance connection is established between the positive and negative terminals. Manufacturers have several safety mechanisms, controls, and interlocks available for use in the design of battery cells, battery packs, and/or the host device to reduce the risk of thermal runaway. Some of these safety mechanisms include a battery management unit (BMU), positive temperature coefficient (PTC) device, and current interrupt device (CID), which are discussed in other literature [10]. If designed, manufactured, and used properly, Li-ion battery cells can serve as a safe power source.

Still, there have been recalls of various Li-ion battery-powered products due to the possibility of overheating and/or catching fire [11–13]. In a 5-year span from 2012–2017 there were over four million Li-ion battery products involved in forty-nine recalls in the United States [14]. The public is becoming familiar with their hazards through videos of Li-ion batteries catching fire and news stories discussing notable incidents [15]. Due to this heightened awareness, any device with a Li-ion battery found in the area of origin of a fire scene will be considered a potential ignition source; however, determining whether a Li-ion battery actually caused the fire is a formidable challenge. A full analysis on the failure modes of Li-ion batteries is beyond the scope of this work, but literature on the matter may be found elsewhere (see Appendix H in Linden's Handbook of Batteries, 4th edition) [4]. When investigating the cause of a fire, the investigator must evaluate all possible ignition sources. Evaluation of the physical evidence is of paramount

importance. The investigator must consider the evidence, and if possible, the chronology of the damage.

While the failure of an 18650 Li-ion cell that results in personal injury or property damage is rare, they are often blamed for causing fires. Li-ion cells have the potential to cause fires, but they may simply be victims of those fires. Determining which of these scenarios is correct is an ongoing challenge for fire investigators; care must be taken to ensure an accurate forensic investigation is performed, adhering to the scientific method [16]. During the course of some litigation matters, forensic engineers and scientists have relied on untested hypotheses that pointed to specific post-fire physical features of a Li-ion cell as evidence that it caused a fire as opposed to the manifestation of those features as a result of fire attack. The following are some examples of these untested hypotheses:

1. Over-pressurization that results in deformation of the crimp indicates cell failure and fire causation.
2. Expulsion of cell contents indicates cell failure and fire causation.
3. A flat negative terminal of the cell enclosure indicates cell failure and fire causation, whereas a convex negative terminal indicates the cell was a victim of the fire.
4. Damage localized to the interior electrode windings compared to the external windings indicates cell failure and fire causation.
5. A hole in the metal enclosure indicates cell failure and fire causation.

While these hypotheses have been repeatedly used in multiple unique fire incidents to draw conclusions by forensic engineers and scientists, they were not supported by peer reviewed scientific literature or experiments. Therefore, Engineering Systems Inc. (ESi) performed extensive compartment fire testing of 18650 Li-ion cells to test these hypotheses and determine if certain post-fire physical cell features imply fire causation or if they may occur as a result of cells being exposed to a compartment fire.

This paper describes the test setup, including the compartment used to test these cells, instrumentation, measurements taken during testing, documentation techniques, test results, and interpretation of results.

2. Experimental Method

The objective of the experimental setup was to enable evaluation of the heat effects of a compartment fire on 18650 Li-ion cells. Testing was performed outdoors in a custom fire test chamber (FTC) that was instrumented with K-type thermocouples. The FTC was designed and intended to repeatably produce radiant heat that would induce thermal runaway in the cells being tested between experimental runs, not to represent any one particular fire condition. Temperature data was recorded to ensure consistent conditions between experiments. Care was taken to ensure the experimental procedure and setup were relevant, reliable, and reproducible. Considerations included the design of the FTC, material and struc-

ture of the fuel load, fire development, method of data acquisition, and evidence preservation.

2.1. *Fire Test Chamber Materials and Construction*

2.1.1. Exterior Frame The frame of the FTC was constructed with 1.5 in $\times$ 1.5 in $\times$ 11 gauge square steel tubing. The left, right, and rear exterior walls were made of $\frac{3}{4}$ in $\times$ #9 flattened expanded metal and the floor and ceiling were made of 12 gauge steel plates. The front was open. The exterior dimensions were 51 in wide $\times$ 50.5 in deep $\times$ 97.5 in tall. The FTC was supported on 5 in tall legs. A diagram is shown in Fig. 2.

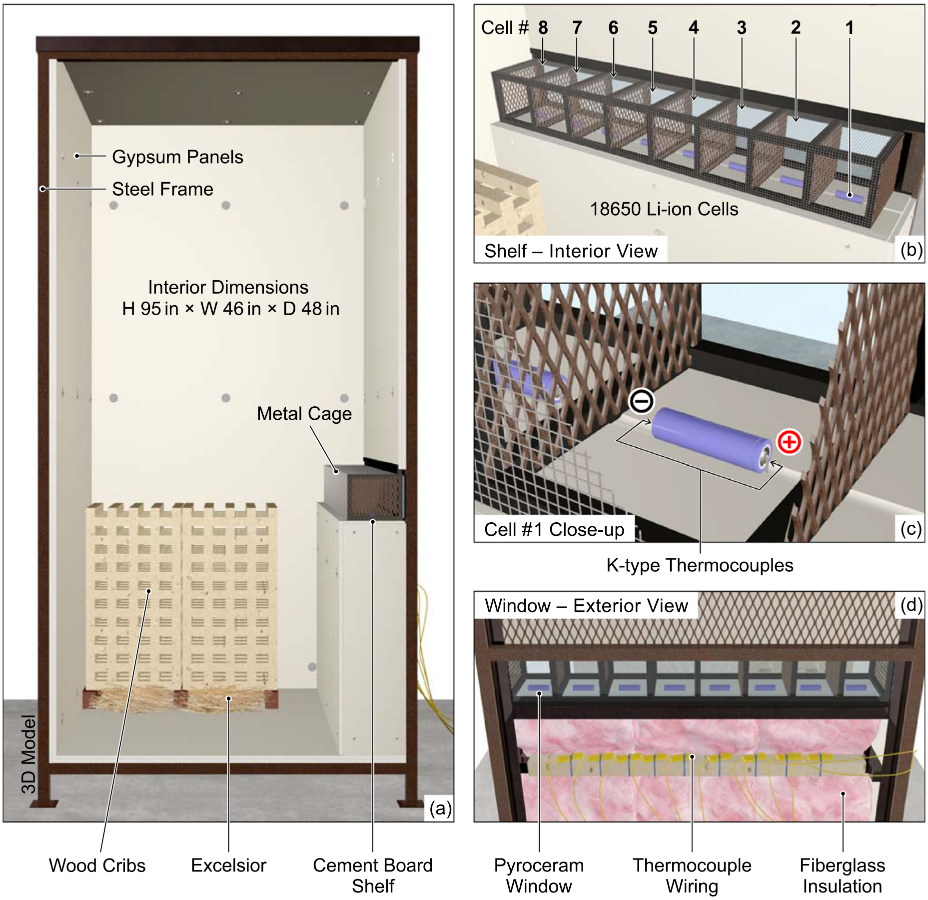

Figure 2. Diagrams of the fire test chamber. (a) Overview of the fire test chamber, front view. (b) Overview of the battery cells under test in their retention cages. (c) Detail of cell orientation and thermocouple placement. (d) Thermocouple routing and Pyroceram window.

2.1.2. Interior Finish The interior surfaces (floor, ceiling, and walls) of the FTC were lined with double layers of 0.5 in × 4 ft × 8 ft United States Gypsum (USG) Brand Sheetrock® UltraLight Drywall (gypsum) Panels. The panels on the walls and ceiling were secured to the expanded metal or steel plates with $\frac{1}{4}$ in × 1.5 in nominal bolts, fender washers, and nuts to facilitate rapid removal and replacement. The interior panels were all replaced before each test. The interior dimensions were 46 in wide × 48 in deep × 95 in tall.

2.1.3. Shelf A slide-in shelf along the right wall of the FTC was constructed of a metal frame faced with a double layer of the aforementioned gypsum panels on its exposed vertical surfaces and a single layer of 0.42 in HardieBacker® 500 Cement Board with MoldBlock® Technology on its top surface. The surface materials were replaced before each test. The shelf dimensions were 9 in wide × 48 in deep × 31.5 in tall. An $\frac{1}{8}$ in deep groove was milled into the top of the cement board surface along its depth to provide a seat for the battery cells under test. A mesh cage on the shelf prevented the cells from leaving the FTC due to an energetic reaction and kept them separate. The shelf interior was insulated with fiberglass batts to provide heat protection for the thermocouple wiring.

2.1.4. Viewing Window A fixed 48 in wide × 6 in tall × $\frac{1}{8}$ in thick Pyroceram (heat-resistant glass-ceramic) viewing window was located on the right wall just above the shelf to enable direct observation and video documentation of the cells during testing.

2.2. 18650 Li-ion Cell Orientation and Labeling

Six rounds of testing were performed, with eight identical cells per test. The cells were removed and separated from new laptop battery packs supplied by the original equipment manufacturer, each of which contained nine cells. The cells under test were aligned coaxially along the groove in the shelf, oriented with their positive "button" ends pointing toward the open front of the FTC. Each cell rested in the groove between two thermocouples but was not held rigidly in place. They were numbered 1 through 8, with cell 1 located closest to the open front of the FTC and cell 8 closest to the rear wall. The details of the cells used in each test are summarized in Table 1. Specific cells are denoted by manufacturer, SOC, and location in the FTC; for example A100-1 represents cell 1 of manufacturer A at a 100% SOC. The layout is depicted in Fig. 2b, c.

2.3. Thermocouple Instrumentation

The cells under test were 65 mm in length and 9 mm in radius. For each cell, two $\frac{1}{16}$ in diameter holes were drilled 65 mm apart along the groove in which the cells rested. K-type thermocouples with $\frac{1}{16}$ in diameter steel sheaths were inserted upward through the surface of the shelf so their tips coincided with the centerline of the cells, approximately 9 mm above the shelf surface. Each cell was then placed in the groove between its respective pair of thermocouples (Fig. 3). The

Table 1
Summary of 18650 Li-ion Cells Used for Testing and Their States of Charge (SOC)

Test ID	Manufacturer	SOC (%)	Capacity (mAh)
A100	A	100	2800
A50	A	50	2800
A30	A	30	2800
B100	B	100	2600
B70	B	70	2600
B50	B	50	2600

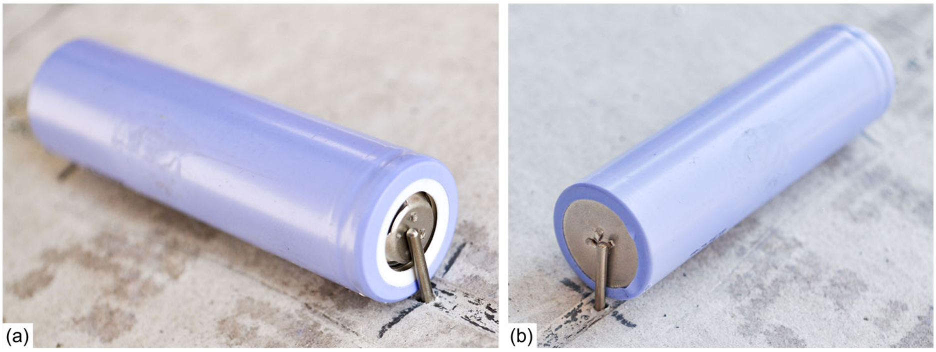

Figure 3. 18650 Li-ion battery cells were placed in a groove with a K-type thermocouple contacting their positive (a) and negative (b) terminals.

thermocouple sheaths were bent slightly toward the cells if necessary, to ensure that the tip of each thermocouple was in good thermal contact with the center of either the positive or negative terminal of the cell.

Three K-type thermocouples were installed in a vertical line along the rear wall, 9 in to the left of the shelf. These thermocouples were inserted from behind the rear wall and protruded approximately 2 in into the FTC at heights of 35 in, 57 in, and 80 in above the floor. One K-type thermocouple was located outside the chamber to monitor the ambient outdoor temperature. A total of twenty thermocouples were used. Temperature data was recorded throughout testing at a sample rate of 1 Hz using an Omega OMB-DAQ-56 data acquisition unit.

The thermocouples were Omega model CASS-116U-12. These thermocouples were not grounded to the outer metal sheath because a pair of thermocouples was in contact with the positive and negative ends of the cells. The thermocouples had a thermal response time of less than 2 s. The fire transferred heat to the cells through radiant energy, and the thermocouples sensed the temperature of the cells through conduction.

2.4. Fuel Load

The main fuel load was wood cribs constructed in accordance with Section 26.302 of the Uniform Building Code Standard 26-3 [UBC-26-3, 1997], which dictates the fire test structure for room fire testing for the interior of foam plastic systems. The cribs were built with Barrette Heat Treated Spruce-Pine-Fir (SPF), which had nominal dimensions of 2 in $\times$ 2 in $\times$ 8 ft and actual dimensions of 1.437 in $\times$ 1.437 in $\times$ 8 ft. The cribs were built with 15 in lengths of the SPF. They were 15 in square in plan with ten tiers having five equally spaced sticks per tier. The sticks in each tier were oriented perpendicular to the sticks in adjacent tiers. The sticks were secured in the specified arrangement with 2.5 in long $\times$ 15 gauge finish nails. The weight of each assembled crib was 28 pounds. After fabrication the cribs were maintained in air-conditioned storage until the time of use in order to maintain a low moisture content.

Four cribs were burned for each test. Two cribs were positioned side by side with partial standard bricks beneath each corner of the cribs. Two additional cribs were stacked on the lower cribs in a manner that maintained the perpendicular orientation between adjacent tiers. This fuel load was positioned in the left rear corner of the FTC approximately 1 in from the left and rear walls. The right side of the cribs was approximately 6 in from the shelf. The three thermocouples along the rear FTC wall were located above and behind the wood cribs, approximately 3 in to the left of their right side.

American Excelsior Company® all-natural aspen wood excelsior was fluffed and distributed on the floor of the FTC around the partial standard bricks and beneath the wood cribs. Six to twelve ounces of Klean-Strip® denatured alcohol were used as an accelerant. The denatured alcohol ensured the excelsior ignited rapidly so the wood cribs would ignite uniformly.

2.5. Ignition

The denatured alcohol was divided into two cans and poured evenly over the top of the wood cribs so they and the underlying excelsior would be wetted. The frontmost portion of the excelsior protruding from under the wood cribs was then ignited with a butane grill lighter. The experiments were performed outdoors near sea level, so adequate oxygen was available from the air and the fire was fuel controlled. The typical fire progression for this experiment is shown in Fig. 4.

2.6. Documentation

Each experiment was documented with still photography during the preparation, burn, and post-burn phases. Five video cameras recorded the entire duration of each experiment. Video cameras 1, 2, 3, and 4 focused on cells 1 and 2, 3 and 4, 5 and 6, and 7 and 8, respectively, through the Pyroceram window. Video camera 5 viewed the interior of the FTC from the front. All video cameras recorded at 15 frames per second at a resolution of either 720p or 1080p.

Detailed post-fire analyses were performed. A CT scan of each cell was taken to preserve its post-fire state and enable non-destructive examination of the physical

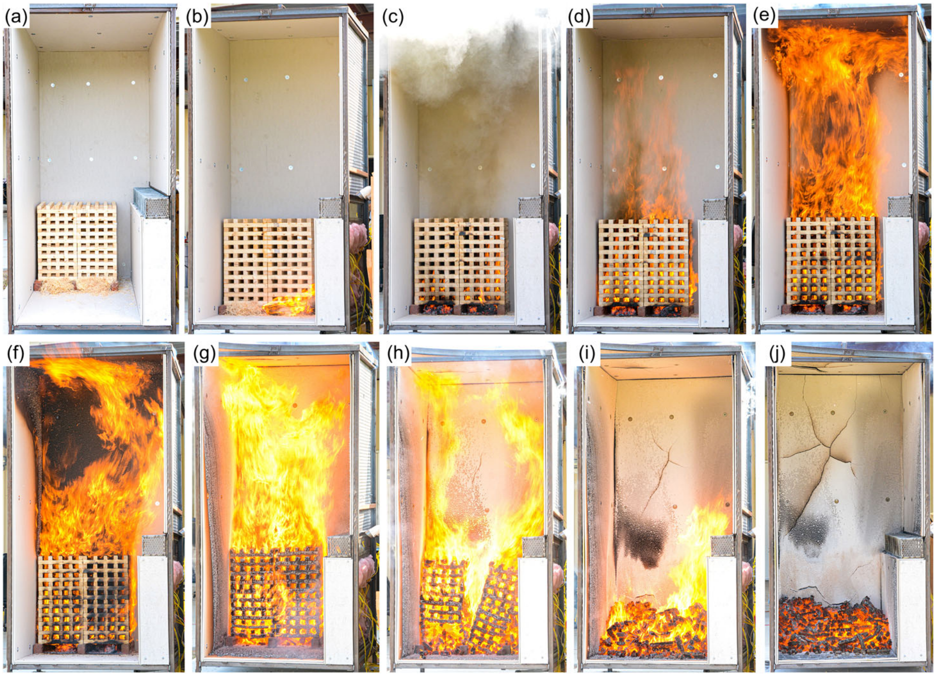

Figure 4. Typical fire progression sequence inside the fire test chamber. 18650 cells are in the cage on the shelf to the right.

fire effects. A CT scan of an unburned exemplar cell from manufacturer A is shown in Fig. 5 for reference. The slightly curved appearance of both the cell's ends in (a) is due to a CT imaging artifact. Other documentation techniques included X-ray imaging, optical photography, and optical microscopy. CT scanning and X-ray radiography measurements were collected with a Nikon XTH 320 CT

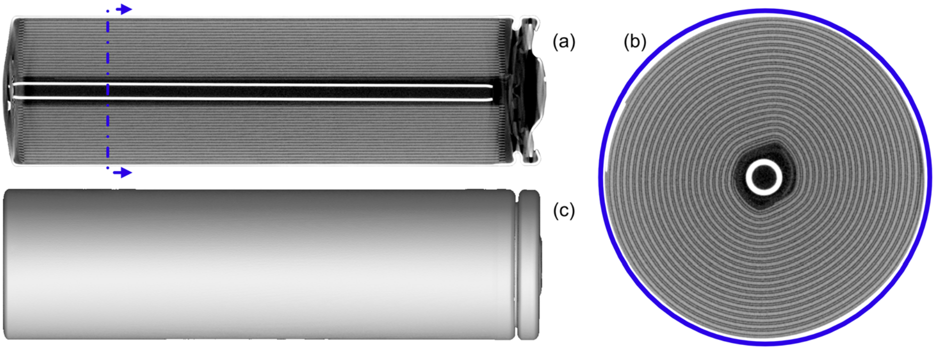

Figure 5. CT scan of an unburned exemplar cell from manufacturer A: (a) lengthwise cross section, (b) axial cross section, and (c) outer surface.

machine, utilizing a 225 kV rotating target. Optical microscopy was performed with a Nikon SMZ-U stereo zoom microscope.

3. Results and Discussion

Cells with four SOC levels—30%, 50%, 70%, and 100%—were exposed to fire in the FTC. Cells with higher SOCs produced more energetic reactions when heated, as expected [17]. The more energetic reactions expelled gas out of the positive terminals with sufficient force to expel the electrode windings and propel the cells from their resting places. CT scans were used to evaluate the type and degree of internal damage, as well as to examine deformation and damage to the metal enclosure.

This paper demonstrates that specific physical features observed on a cylindrical 18650 Li-ion battery cell at the scene of a fire do not necessarily indicate that the cell failed and caused the fire. Each of these physical features were successfully produced in cells that were intentionally burned, indicating that these features are not indicative of cell failure and/or fire causation. The findings are detailed in the following sections.

3.1. Crimp Deformation

The metal enclosure of a cylindrical 18650 battery cell is crimped inward above the electrodes and below the positive cap assembly, securing their positions within the enclosure as shown in Fig. 6. The positive cap assembly is electrically isolated from the enclosure with an insulating gasket (Fig. 6). During a fire, hot gases expand in the cell, applying pressure to the battery cell enclosure. The vent in the

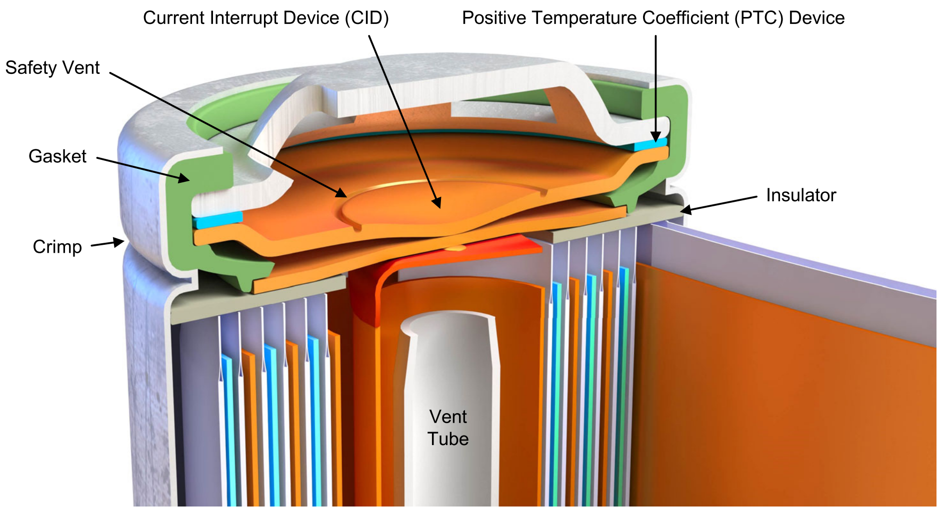

Figure 6. Rendered cross sectional view of an 18650 cell positive terminal cap assembly.

positive top cap assembly can exhaust this pressure, but if the pressure builds too quickly or the vent is blocked by escaping debris, the crimp may deform. In some cases, crimp deformation is accompanied by expulsion of the positive top cap assembly and electrodes.

Crimp deformation was observed in cells that were victims of a fire. Two cells from the A100 test had significantly deformed crimps and expelled their positive terminal caps. Six B100 cells had significantly deformed crimps, four of which expelled their positive cap assemblies. Significant crimp deformation was observed almost exclusively in the A100 and B100 tests; however, cell A50-2 also experienced significant crimp deformation accompanied by expulsion of its positive cap assembly. Several other cells experienced a small amount of crimp deformation, but not enough for the positive cap assembly to be expelled. Some examples of crimp deformation are shown in Figs. 9 and 13. The B50 cells were the only ones that did not exhibit noticeable crimp deformation. Deformation of the crimp therefore is not exclusive to internal cell failure and does not indicate fire causation.

3.2. Expulsion of Electrode Windings

Cells that are victims of a fire may partially or completely expel their electrode windings (Fig. 7). Three cells from Manufacturer B with a 100% SOC—B100-1, B100-4, and B100-8—completely expelled their electrodes. A cross sectional CT scan of cell B100-8 is shown in Fig. 9. Cells from the B70 and B50 tests did not expel their positive cap assemblies or electrodes.

Only one of the cells from Manufacturer A (cell A100-7) completely expelled its positive cap assembly and electrodes. Cell A100-2 expelled its cap and partially expelled its electrode windings. Cells A100-6 and A100-8 retained their positive cap assemblies, but the vent tube and upper portion of the electrodes were driven through the cap such that they were partially protruding. Cell A100-8 is shown in Fig. 7. Cell A50-2 expelled its cap and partially expelled its electrode windings, which were left protruding from the enclosure. The rest of the cells retained their windings, though many of them were displaced towards the positive terminal cap. Partial or complete expulsion of electrodes are therefore not exclusive to an internal cell failure and should not be relied upon as indicators of fire causation.

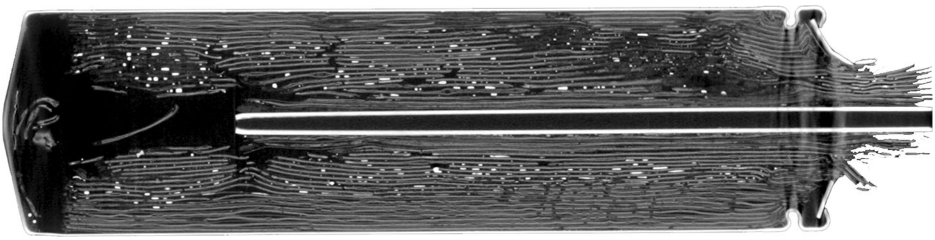

Figure 7. CT scan of cell A100-8. The vent tube and some electrode windings were pushed through the positive terminal cap during testing.

3.3. Negative Terminal Deformation

The sealed flat end of the metal cell enclosure, which is the negative terminal, can expand outward and become convex when cells are victims of a fire due to overpressurization of the enclosure; however, cells that are victims of a fire may also retain their flat negative terminals. Both conditions were observed in the experiments presented in this work, as shown in Fig. 8; the majority of the negative terminals remained flat. Cells exhibiting convex negative terminals all had a 70% SOC or higher and did not completely expel their positive terminal caps or electrode windings. Manufacturer B cells with a 100% SOC exhibited the most frequent convex negative terminal deformation.

In some cases, the negative terminal collapsed inward. This occurred in six cells that partially or fully expelled their electrode windings. Three cells from Manufacturer A—A100-2, A100-7, and A50-2—exhibited collapsed negative terminals and partial windings expulsion. Three cells from Manufacturer B—B100-1, B100-4, and B100-8—exhibited collapsed negative terminals and complete windings expulsion. This likely occurred when mechanical force was applied to the negative terminal by either the stainless steel thermocouple sheath or impact with the retaining cage around the cells when they moved during the rapid expulsion of their windings from their positive terminals. Cell B100-8 is shown in Fig. 9.

3.4. Localized Damage in Electrode Windings

Cells that are victims of a fire may have damage localized to their inner or outer electrode windings or may have continuous damage throughout. All three scenarios were observed during testing. A CT scan of a cell with damage localized to its inner windings, cell A50-3, is shown in Fig. 10. The damage appeared as two toroidal voids, one directly around the vent tube and one closer to the positive terminal with a slightly larger radius. Cells A50-5 and A50-8 had damage localized to their outer electrode windings in the form of lengthwise voids adjacent to their enclosures. A CT scan of cell A50-5 is shown in Fig. 11. In many cases there is damage throughout the electrode windings, such as in B50-3; a CT scan of its

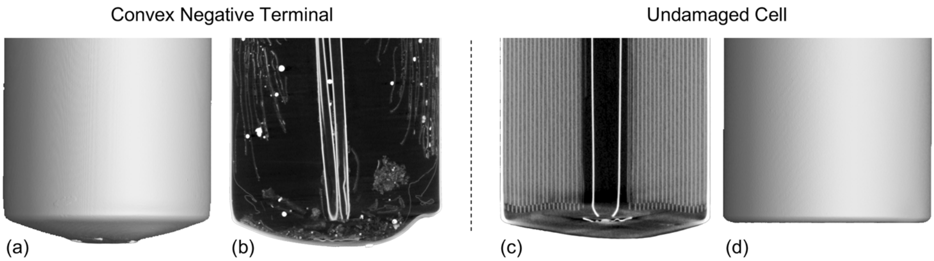

Figure 8. CT scans of cells B100-3 (a, b) and B70-1 (c, d). The negative terminal of B100-3 became convex, while B70-1 remained flat. Note that CT imaging artifacts cause the flat bottom of B70-1 to appear slightly convex in (c).

Figure 9. CT scan of cell B100-8. The negative terminal collapsed inward and the crimp deformed during testing.

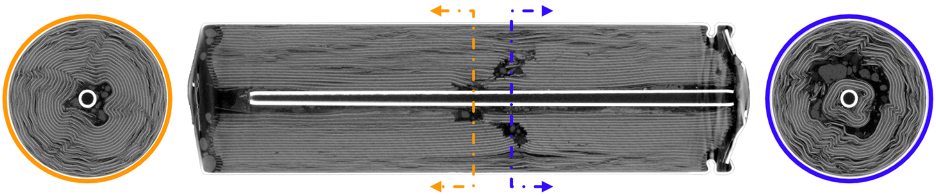

Figure 10. CT scan of cell A50-3. Cross sectional views of two localized regions of inner electrode windings damage.

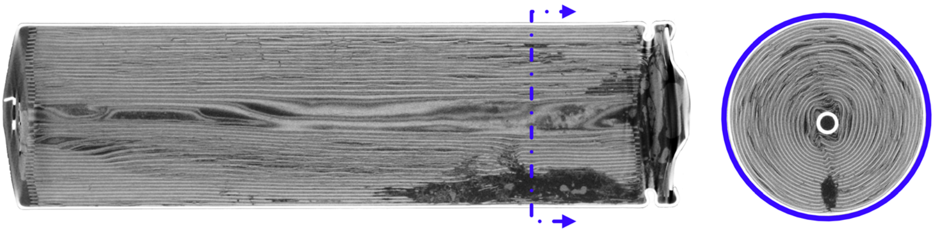

Figure 11. CT scan of cell A50-5. Cross sectional view of localized outer electrode windings damage.

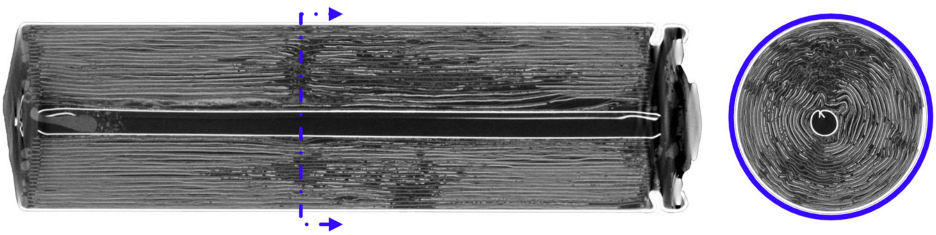

Figure 12. CT scan of cell B50-3. Cross sectional view of damage throughout electrode windings.

windings is shown in Fig. 12. Localization of electrode windings damage therefore does not indicate whether a cell was the cause or a victim of a fire.

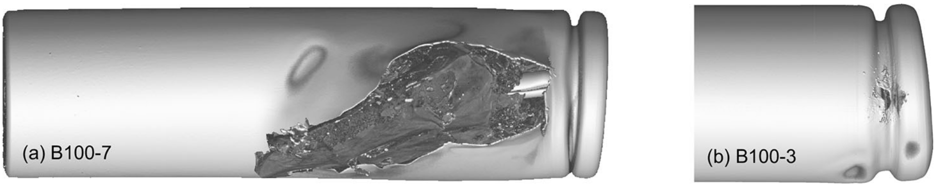

Figure 13. CT scans of cells B100-7 (a) and B100-3 (b) showing holes that formed in their enclosures during testing. The crimps of both cells also deformed during testing.

Figure 14. Photographs of the (a) outside of the enclosure, (b) inside of the enclosure, and (c) expelled contents of cell B100-6. The enclosure split open during testing.

3.5. Hole in the Metal Enclosure

A hole may be melted through the metal enclosure from the inside of a cell that is the victim of a fire. In the 100% SOC tests for both manufacturers, three out of eight cells had holes melted through their enclosures. While Manufacturer A cells had small holes on the order of one square centimeter located around their crimps, Manufacturer B cells sustained more substantial damage. Cell B100-7 had a large hole that covered half of one side, while B100-3 had a small hole in the crimp (Fig. 13). Cell B100-6 exploded and was reduced to a flattened scrap of metal (Fig. 14). Two Manufacturer B cells with lower SOCs also had holes melted through their enclosures: cell B70-5 had two small holes melted through the corner of the negative terminal and cell B50-8 had a hole melted in and around its positive terminal cap. None of the Manufacturer A cells with less than 100% SOC exhibited melted holes in their enclosures.

4. Conclusions

This paper examined several post-fire physical features on 18650 Li-ion cells that are commonly cited as indications of cell failure and fire causation. Cells from two different manufacturers with different SOCs were intentionally burned in a repeatable fashion to determine if these physical features could occur when the cells

were victims of a fire. The following conclusions were drawn based on the experimental results presented in this manuscript:

1. Overpressurization that results in the deformation of the crimp can occur in cells that are victims of a fire and does not indicate fire causation.
2. Expulsion of cell contents can occur in cells that are victims of a fire and does not indicate fire causation.
3. The negative cell terminal may remain flat or become convex when a cell is a victim of a fire; negative terminal shape does not indicate whether a cell caused a fire or was a victim.
4. Localized electrode windings damage does not indicate fire causation. Damage may be localized to the inner region, outer region, or spread throughout the windings of cells that are victims of a fire.
5. A hole in the metal enclosure can occur in cells that are victims of a fire and does not indicate fire causation.

To summarize, all of the post-fire physical features in question were observed multiple times during these experiments where cells were known victims of fires that were intentionally set. Therefore, these features should not be considered reliable indicators of fire causation.

Acknowledgements

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